Addressing global environmental megatrends by decoupling the causal chain through floating infrastructure

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Keywords

Global Megatrends, Climate Change, Adaption Strategies, Renewable Energy, Aquaculture, Urban Expansion

Introduction

The term megatrend was coined by Naisbitt in the 1980s to describe large scale developments in individual, social or technological structures effecting society and economies in the decades to come. He was convinced that, in order to predict the future, one has to understand the present. Thus, by analyzing current developments and trends, a number of larger, more general megatrends could be discerned, which may significantly influence the shape of the world of tomorrow (Naisbitt, 1982). This attempt at predicting future developments has become important for academia as well as industry, for instance in order to properly prioritize research projects or strategic decision making (Cuhls, Bunkowski, & Behlau, 2012; Utikal & Woth, 2015). Consequently, there are numerous studies and reports by academics, industry groups and also governments dealing with the topic of trends and megatrends. In this paper we first describe the most essential global megatrends and connect them to on one another though a causal chain, starting with global population growth and ending with an increasing global potential for conflict. The unprecedented increase in global population and the consequentially increasing pressure on available resources such as food, water, minerals or even space are the main drivers for many if not all of the major challenges which humanity will be facing in the coming decades. A major consequence of these increasing levels of global resource demand is climate change and all its associated effects (Intergovernmental Panel on Climate Change, 2018). Governments (and corporations) around the world have begun to understand the magnitude of the disruptions to society that will occur if nothing is done to alter the trajectory the world has been taking in the past decades. Therefore, strategies to limit the effects of climate change and to cope with the inevitable changes in global climate already happening are currently of central interest to academic as well as industrial research. In the second part of this paper we introduce the concept of floating construction as such a climate change mitigation and adaption strategy. Using the presented causal chain we highlight and discuss these areas where floating construction may have a positive impact on global developments in the mid- to long-term future.

A Schematic Causal Chain for Global Future Challenges

Cause: Population Growth and Increasing Urbanization

In line with increasing wealth and knowledge advances in all areas of science, the global population has completed a period of staggering growth in the last 25 years growing from 5.3 billion in 1990 to 7.6 billion in 2018. Although the annual population growth rate is expected to decrease slightly throughout the course of the century, the medium population estimate for 2050 and 2100 are 9.8 and 11.2 billion respectively. As the demand for any good, be it food, energy, space and also services such as healthcare, scales with the number of existing consumers, the growing global population is the main driver of most large scale future developments. In addition to this explosive population growth, global urbanization rates are also drastically increasing (from 55% in 2018 to 68% by 2050). Cities, as the largest consumers of resources and emitters of waste, will have to grow in one way or another to accommodate this huge influx of people putting additional pressure on available resources and land (United Nations, Department of Economic and Social Affairs, 2015, 2018). Furthermore, the economies of scale offered by such concentrated urban centers enable increased productivity and the associated economic growth which further drives the overall increase in demand (McKinsey Global Institute, 2011). Consequently, these two global developments form the starting point of the causal chain shown in Figure 1, leading to an increasing demand for food, mineral resources and energy.

Direct Effect: Increasing Food, Energy and Resource Demand

The production of food with enough calorific value to sustain today's global population takes up 20% of globally available landmass. Nevertheless, there are still 768 Million people worldwide that cannot get access to sufficient amounts of food (Food and Agriculture Organization of the United Nations, 2015). Inequality in distribution is a major cause of malnutrition. Nevertheless, redistribution of current supply is not enough to sustain the ever increasing global population. Even increases in production yield may prove insufficient (Bajželj et al., 2014). With increases in global demand for crops ranging from 70% (Alexandratos & Bruinsma, 2012) to 100% (Tilman, Balzer, Hill, & Befort, 2011) from the year 2005 until 2050, an increase in global production volumes is unavoidable. With declining growth rates of global agricultural efficiency, a significant part of this increase will need to come from expansion of agricultural areas (Ray, Mueller, West, & Foley, 2013). Although the negative effects are well known even today, the clearing of natural forest represents the dominant approach to increasing available agricultural space especially in developing countries. The burning of these often huge areas of vegetation not only releases CO_2 into the atmosphere, but also simultaneously reduces the area's CO_2 storage potential (Houghton, 2012). Food demand is not driven solely by population growth, but also by the globally predicted increasing levels of wealth and the associated move towards a more protein heavy, higher calorie diet (Alexandratos & Bruinsma, 2012; Gerber, Steinfeld, Henderson, Mottet, & Opio, 2013; Tilman et al., 2011). As the raising of livestock, specifically cattle, not only requires significantly more resources per calorie than the cultivation of crops, but is also responsible for 14.5% of global greenhouse gas (GHG) emissions and 44% of global methane emissions (Gerber et al., 2013) food production will be a strongly increasing contributor to global GHG emissions both directly and indirectly and will take up more and more space on the global landmass if no radical changes occur.

Next to nutrition, nonrenewable mineral resources are paramount to human development and economic growth. Extraction and processing of these resources require large amounts of energy and produces large volumes of hazardous waste. Therefore, increasing demand will directly lead to increased emissions and effluents. Next to these developments extensive extraction of mineral resources has accelerated the depletion of existing high grade deposits around the globe forcing the industry to move to deposits of lower grade minerals (Northey, Mudd, & Werner, 2018). Thus, larger areas need to be mined in order to obtain the required volumes of final raw material making an increasing amount of space unusable for other essential functions such as agriculture or housing. Furthermore, the extraction of lower grade ores also requires significantly more water and energy consequently producing more waste, adding to the increase in harmful emissions (Mudd, 2007). Decreasing reserves of certain mineral resources may also lead to issues of scarcity in global markets, increasing the potential for conflict between exporting and importing countries (European Commission, 2014).

Along with the direct need of a growing population for heat, electricity and fuel, global energy demand is further increasing due to the mentioned developments affecting food and mineral resources. Energy has always been and will continue to be a key enabler of and also a requirement for economic growth. Global energy use is estimated to increase by one third from 2015 to 2040. Despite increasing international efforts to increase the share of energy generated from renewable sources, the majority of today's energy is supplied by nonrenewable fossil fuels, dominated by oil and coal but also to a growing extent natural gas (International Energy Agency, 2015). Continued expansion in the use of fossil fuels will not only lead to massive global GHG emissions but also require extensive amounts of space for extraction, processing and conversion of these fossil resources to energy.

Indirect Effect: Global Warming, Sea Level Rise and Conflict

The most concerning effects of the emissions associated with the growth of the three previously mentioned sectors are commonly summarized under the term climate. In this paper we focus on one of the most severe effects of climate change, i.e. sea level rise, caused by the melting of the planet's ice masses and thermal expansion of the oceans as a consequence of increasing global temperatures (Church, Gregory, White, Platten, & Mitrovica, 2011; Pachauri & Mayer, 2015).

Depending on the future levels of global GHG emissions, sea levels are expected to rise between 0.3 m and 2 m by 2100 (Pachauri & Mayer, 2015). It has been estimated, that, as a consequence, in the United States alone between 4.2 and 13.1 million people will be put at risk of inundation (Hauer, Evans, & Mishra, 2016). Globally this number will be significantly higher as all low lying coastal regions are affected. The amount of capital and population at risk from floods has increased dramatically in recent years, and despite the construction of flood protection measures such as dikes, dams or sea walls the yearly average global flood damage more than doubled from 12.7 billion $ in 1995 to 31.7 billion $ in 2015 as shown in Figure 2 (Guha-Sapir, Below, & Hoyois, 2016). As it is expected that half the global population will live within 100 km of the coast by 2030 and the global number of flooding events is increasing, these numbers will increase even further in the next decades (Adger, Hughes, Folke, Carpenter, & Rockstrom, 2005; Brakenridge, 2016). Increasingly severe incidents of flooding however do not only directly cause great damage and loss of life but may also have extensive long-term effects by increasing the salinity of the soil in the affected area, destroying valuable farm land (Smajgl et al., 2015). An extreme consequence of the combined effects of severe flooding events and a decreasing global landmass is the forced relocation of entire populations, as is already the case in certain regions in the southern Pacific (Albert et al., 2016; Kumar & Taylor, 2015). These new groups of refugees essentially fleeing from the effects of climate change will need to move to more suitable locations which tend to be existing towns or cities. The affected cities which are already expanding at a rapid rate due to other factors, will need to accommodate yet more inhabitants.

A report by de Graf estimates that the global average urban density in 2012 was 1750 inhabitants/km^2. If this density were to remain constant the addition of 5 billion people (excluding climate refuges) to the global urban population by 2100 would require an expansion of these areas by a total of 2.85 million km^2, more than half the total land area of the European Union. The report further estimates the globally available agricultural land to amount to 16 million km^2. If urban expansion were to come at the expense of agricultural land which surrounds most large cities, this would mean a reduction of global farm land by 18%. To compensate for this reduction in available land and still meet the increasing demand for food, an annual productivity growth of 2 – 2.4% would be required over the next 38 years (de Graaf, 2012). However, as already mentioned, the growth rate of global cereal production yield has been declining over the past decades and the majority of simulations show that they will continue to do so throughout the century especially in the face of increasing temperatures again resulting from climate change (Challinor et al., 2014). Looking at these numbers it is clear, that at the current levels of urban density cities cannot expand far enough into agricultural land to accommodate the increasing population without severely impacting food supply security. Therefore, the only viable solution in the long term will be to increase the population density of urban areas. High population densities have been shown to be strong predictors of increased conflict potential on a local and regional level due to an increased competition for scarce resources and the fact that densely populated areas provide greater opportunities for financing and organizing of conflict (Raleigh & Urdal, 2007). Consequently, all previously mentioned developments, which ultimately are a result of an increasing global population and rising rates of urbanization, culminate in a globally increasing potential for conflict that may reach international scales (Barnett, 2003; Schwartz & Randall, 2003).

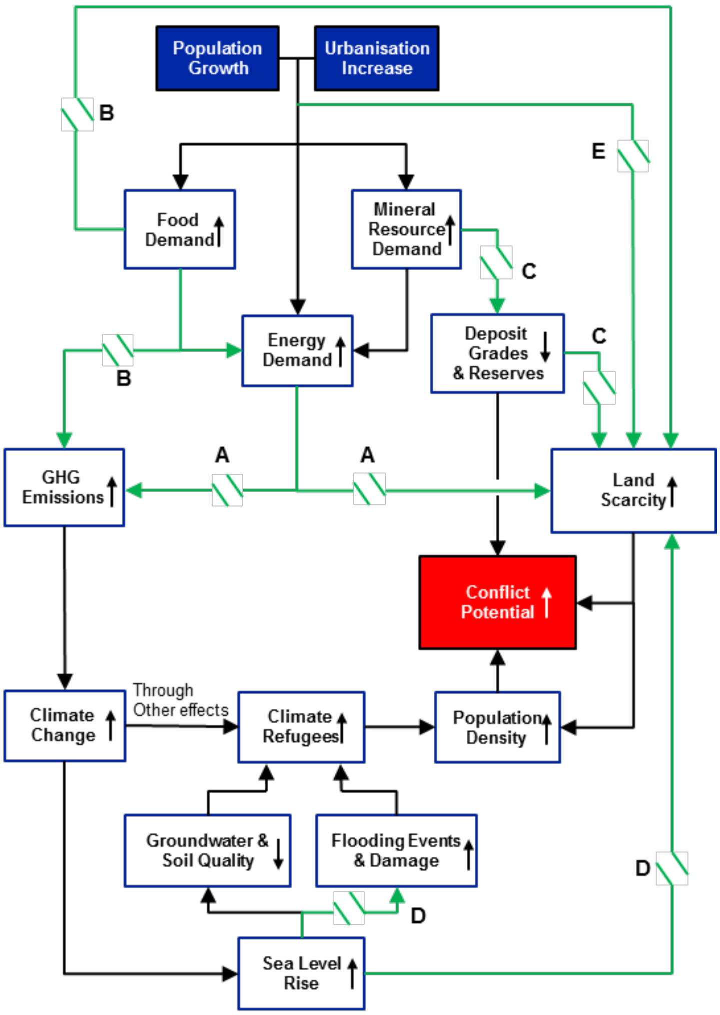

Fig. 1: The chain of cause and effect of global warming and sea level rise with direct (D,E) and indirect (A,B,C) decoupling of cause and effect through floating construction

Addressing the Global Challenges

The complexity of the interactions leading up to and resulting from global climate change make it clear that this challenge cannot be solved with a single approach or solution. On the contrary, a combination of various different technical, economic and social developments will be necessary. Consequently, the development of clean technologies and implementation of mitigation and resilience strategies is currently of central importance in many countries. Most individual strategies or technologies however focus mainly on decoupling the cause and effect between two specific developments (i.e. boxes) in the presented causal chain (Figure 1). Examples are renewable energy technologies aiming at decoupling emissions from energy demand, research aimed at increasing agricultural efficiency, which may decrease land and energy requirements for food production with a specific calorific output, or the development of recycling technologies which reduce the demand for virgin mineral resources. Next to these developments, which all are essential for achieving a sustainable future, floating infrastructure presents itself as an additional highly effective strategy.

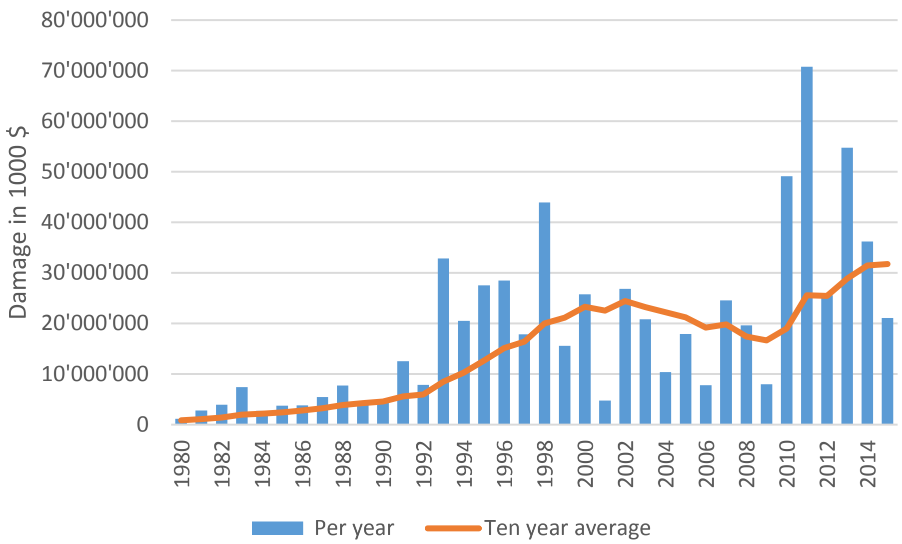

Fig. 2: Development of yearly global flood damage (Guha-Sapir et al., 2016)

Interrupting the Causal Chain through Floating Construction

Looking at Figure 1, one can demonstrate that floating construction has the potential to interrupt multiple connections in the causal chain by acting as a supporting as well as a standalone technology. As an auxiliary technology floating infrastructure can play an important role to help improve the performance of already more established research fields such as renewable energy generation, aquaculture and the extraction of alternative mineral deposits. The respective connections in the causal chain that are affected by these applications are marked in Figure 1 with A, B and C respectively. The concept of building on water furthermore offers a promising strategy to increasing the resilience of existing as well as future cities and communities to the direct effects of global warming induced sea level rise by rendering buildings immune to flooding (D) and by providing access to the vast unoccupied areas of the global oceans (E). The technologies that may decouple the mentioned links and the benefits of floating construction for these technologies are depicted in Table 1 and will be discussed in detail in the next chapters. The offshore oil and gas industry has been developing large floating structures for decades to drill for resources in deep waters. The adaption of these large scale floating structures to other applications has been slow and only a limited amount of examples exist to date, mainly due to the lack of economic viability. Nevertheless, with changing environmental values, regulations and further technological developments the huge potential this approach can have on a global scale may well be unlocked. For a review on the research related to these very large floating structures see Wang & Tay (2011), Lamas-Pardo, Iglesias & Carral (2015) or Wang & Wang (2015).

Table 1: Cause and effect of global megatrends and the impact of floating construction

<table>
<tr><th>Cause</th><th>Effect</th><th>Approach to Cut/Weaken Link</th><th>Benefit of Floating Technology</th></tr>
<tr><td>Population Growth and Increasing Urbanization</td><td>Land Scarcity</td><td colspan="2">Transition/expansion of infrastructure onto water</td></tr>
<tr><td rowspan="4">Increasing Food Demand</td><td>Land Scarcity</td><td rowspan="3">Marine aquaculture (organisms are more efficient feed-to-biomass converters than livestock and require no freshwater resources)</td><td rowspan="4">Required for move off-shore to establish, larger, more efficient farms, with lower environmental impact than near shore aquaculture</td></tr>
<tr><td>Increasing Energy Demand</td></tr>
<tr><td rowspan="2">Increasing GHG Emissions</td></tr>
<tr><td>Algae as feed for cattle to reduce methane emissions</td></tr>
<tr><td rowspan="7">Increasing Energy Demand</td><td>Land Scarcity</td><td colspan="2">Off-shore energy generation</td></tr>
<tr><td rowspan="6">Increasing GHG Emissions</td><td>Solar energy</td><td>Large areas of space available on water bodies</td></tr>
<tr><td rowspan="3">Wind energy</td><td>Majority of global power generation potential located in deep water</td></tr>
<tr><td>Improved wind conditions off-shore</td></tr>
<tr><td>Lower impact on local communities (noise/view)</td></tr>
<tr><td>Ocean energy</td><td>Higher power generation potential in deeper water</td></tr>
<tr><td>Energy from biomass</td><td>Enables large scale production of algae (high material yield)</td></tr>
<tr><td rowspan="2">Increasing Demand for Mineral Resources</td><td>Declining Deposit Grades and Reserves</td><td rowspan="2">Mining of deep sea mineral deposits</td><td rowspan="2">Larger off-shore processing plants improve cost efficiency</td></tr>
<tr><td>Land Scarcity</td></tr>
<tr><td rowspan="2">Climate Change and Sea Level Rise</td><td>Land Scarcity</td><td colspan="2">Transition/Expansion of Infrastructure onto water</td></tr>
<tr><td>Increasing Flood Damage</td><td colspan="2">Construction of resilient floating infrastructure</td></tr>
</table>

Decoupling carbon emissions from energy demand (A)

A step towards decreasing carbon emissions is the use of carbon neutral, sustainable energy and fuel sources. Power plants that generate energy from sustainable sources such as wind, hydro or solar are increasing in number and size, with government subsidies and new technological developments enabling sinking costs of installation and operation. The International Energy Agency estimates that energy from renewable sources will reach a share of over 25% in the USA, 30% in Japan and China and even 50% in the European Union by 2040 (International Energy Agency, 2015). The main disadvantage of renewable energy sources is that they have an extremely low energy density in comparison with non-renewable sources such as coal or natural gas (Table 2). Consequently, if global energy demand is to be covered entirely from renewable sources in the future an extensive amount of space will be required to install the necessary energy generation capacity (Andrews, Dewey-Mattia, Schechtman, & Mayr, 2011). Floating technology provides the opportunity to move these large scale plants onto the globally widely available water surfaces and provides a number of specific benefits to the individual technologies.

Table 2: Energy density of selected sources (adapted from Layton, 2008)

Source	J/m^3
Solar	**0.0000015**
Geothermal	**0.05**
Wind at 5 m/s	**7**
Tidal Water	**0.5 - 50**
Oil	**45‘000‘000‘000**
Gasoline	**10‘000‘000‘000**
Natural Gas	**40‘000‘000**
Fat (Food)	**30‘000‘000**

Moving wind power generation off-shore has two advantages aside from land use considerations. The first is that wind turbines located offshore may achieve wider acceptance from the local population as the impacts concerning their visual aspects and the noise they emit are limited. More importantly however, offshore wind has a higher energy generation potential then on land due to more constant, less turbulent, and higher speed winds (Breton & Moe, 2009; Henderson et al., 2003; Sun, Huang, & Wu, 2012). Globally there is an enormous potential for offshore wind with estimates of 1600 GW in Japan (Govindji, Rhodri, & Carvallo, 2014), 4150

GW in the USA (U.S. Department of Energy, 2011) and 5000 GW for Europe (European Wind Energy Association, 2013). Most of this potential (80% for Japan and Europe and 60% for the USA) is located in deeper waters exceeding depth of 60 m. Constructing bottom fixed foundations becomes highly uneconomical at such water depth (James & Costa Ros, 2015). According to the European Wind Energy Association (EWEA) the development and installation of floating wind turbines is the only viable approach providing the necessary cost savings to gain access to these vast energy resources. The EWEA further estimates that the energy that could be captured with floating turbines in the deep waters of the North Sea alone would be sufficient to cover four times the demand of the EU thus highlighting the effect floating construction will have on the expansion of this clean energy technology (European Wind Energy Association, 2013).

Aside from the more established renewable energy technologies for sun and wind there is another huge alternative energy source which can be captured offshore - the power of the ocean itself. Ocean power is composed of energy present in the ocean in the form of waves, tidal movements and currents, as well as salient and thermal gradients (Mofor, Goldsmith, & Jones, 2014). The theoretical power generation potential of these different sources is gigantic, estimated at 500 GW of technical potential for wave energy, 1 TW for tidal currents and up to 30 TW for Ocean Thermal Energy Conversion (OTEC) (Kempener & Neumann, 2014c; Pérez-Collazo, Greaves, & Iglesias, 2015; Rajagopalan & Nihous, 2013). Nevertheless, even the most advanced systems for harnessing these power sources are still in the early stages of development. Only a handful of prototypes of these systems are in existence worldwide and the installed capacity is minuscule compared to what may be possible in the future (Table 3).

Table 3: Comparison of global technical potential and installed capacity for ocean energy generation

	Wave Energy[A]	Tidal Energy[B]	OTEC[C]
Technical Potential [MW]	**500'000**	**1'000'000**	**30'000'000**
Installed Capacity [MW]	**6.32**	**520**	**1.32**

A:(Kempener & Neumann, 2014b), B: (Kempener & Neumann, 2014c), C: (Kempener & Neumann, 2014a)

Once again floating construction may significantly contribute to the growth of these energy generation technologies. For instance, as average wave power is generally higher in deeper waters (Falcão, 2010) floating approaches are very promising for the development of wave energy conversion systems and accounted for 67% of devices and concepts being developed in 2014 (Kempener & Neumann, 2014b). The same is true for OTEC, the ocean energy resource with the highest technical potential. OTEC produces energy by using the temperature difference (minimum around 20 °C) between the warm surface water of the ocean and the cold water at depth ranging from 800 – 1000 m. Consequently shore based plants are limited to areas where the topography allows access to waters of such depth directly offshore. For floating OTEC plants on the other hand suitable areas on the open ocean total about 60 million km^2 (Pelc & Fujita, 2002).

So far, all of these offshore energy generating technologies have only been tested as individual prototypes at different scales. The promising results show that these technologies will play an important role in the power generation of the future (Mofor et al., 2014). The next step towards global floating renewable energy generation will be cost reduction measures through learning effects and increasing size of the individual systems. In the longer term plans are being developed to build not only single devices but entire arrays potentially combining different power generation methods to further improve the economics of such operations and harness the vast amounts of energy that are available on and in the ocean (Kalogeri et al., 2017; Pérez-Collazo et al., 2015).

A further highly promising source of energy gathered from the ocean is the production of third generation biofuels from algae. Additionally certain types of algae can also be used as fish feed for aquaculture, human food or even in certain pharmaceutical applications. This high variety of applications is why the market for large scale algae farms may increase significantly in the future (Ghadiryanfar, Rosentrater, Keyhani & Omid, 2016). In fact due to the high material yield of algal growth compared to land based plants previous studies have found that the potential amount of ethanol producible from globally grown algae is nearly four times higher than the most produced land based biofuel crop (Adams, Gallagher & Donnison, 2009). These advantages of large scale algae production will be explored in more detail in the following subchapter on food production.

Reducing carbon emissions and land use intensity of food production (B)

Another critical issue which will need to be solved to enable a sustainable future for mankind is achieving global food security without increasing land use and GHG emissions of the agricultural sector. In the eyes of many experts the oceans will play an important role in feeding the growing world population in the future (Food and Agriculture Organization of the United Nations, 2016; Kutty, 2010; Troell et al., 2014). Half of the globally produced biomass originates from the ocean. However, food from marine sources only accounted for 2% of global human consumption in 2006 (Duarte et al., 2009). Aquaculture - the cultivation of aquatic plants and animals for food purposes - is growing at a rapid pace of around 7.5% per year and accounted for 44% of aquatic food production in 2014. Despite this development, the global aquaculture production volume of 74 Mt is still far behind the levels of global land based agricultural and livestock production which amounted to over 7250 Mt in 2004 (Duarte et al., 2009; Food and Agriculture Organization of the United Nations, 2016). The continued increase of the share of aquaculture in global food production is of paramount importance if future populations are to be supplied with sufficient amounts of food in a sustainable manner. This is due to the fact that marine organism are more efficient feed-to-biomass converters than warm blooded terrestrial animals (Gjedrem, Robinson, & Rye, 2012). For instance, cattle and pigs require 7 and 4 kg of grain concentrate resp. to produce 1 kg of meat while for fish less than 2 kg are required. To produce 1 kg of grain required to feed livestock roughly 1000 l of water are used (Brown, 1999, 2001). Consequently, as fish and other marine animals are considered good sources of nutrients containing high levels of protein comparable with red meat as well as omega-3 fatty acids and high concentrations of vitamins and minerals (McManus & Newton, 2011), aquaculture presents a far more efficient solution to meeting growing protein demands than further expanding land-based livestock production. The greatest benefit is provided by aquaculture conducted in the ocean with species accustomed to salt water as this does not put additional pressure on already shrinking freshwater resources and doesn't further occupy valuable space on land (Verdegem, Bosma, & Verreth, 2006). However, in coastal regions space for aquaculture farms is already getting scarce since it competes with public use of this space. Furthermore, extensive near shore aquaculture has detrimental effects on the local environment such as eutrophication, pollution from waste or transmission of disease to wild species (Duarte et al., 2009; Grigorakis & Rigos, 2011; Marra, 2005). The construction of floating farms offshore provides the opportunity to increase aquaculture production while minimizing these negative effects. The stronger currents and larger water masses in offshore locations allow for a greater natural dilution and dispersion of waste and the installation of larger, especially deeper cages which has been shown to lead to an increase in growth rate and decrease in mortality of the cultivated species (Addis et al., 2010; Marra, 2005; Pogoda, Buck, & Hagen, 2011; Sveälv, 1988). Consequently, the largest future environmentally sustainable expansion of aquaculture is believed to take place further offshore in the oceans potentially reaching as far as the high seas (Food and Agriculture Organization of the United Nations). Unsurprisingly, interest in the development of floating solutions for aquaculture has increased significantly (Loverich, 2010; Marra, 2005; Olanrewaju, Magee, Kader, & Tee, 2016; Stevens, Plew, Hartstein, & Fredriksson, 2008; Sulaiman et al., 2013). An example of the endeavor to move aquaculture offshore is the establishment of Ocean Farming, a subsidiary of the Norwegian SalMar group. Ocean Farming is currently building a full scale prototype of a semisubmersible off shore fish farm for the cultivation of salmon (SalMar ASA, 2016). As salmon farming has become a very important industry for the Norwegian economy with a total production of 1.2 Mt in 2014, the government is attempting to realize the high growth scenario of increasing the countries salmon production to around 5 Mt by 2050 (Hersoug, 2015). According to Ocean Farming this ambitious goal will require 7-8 floating farms to be built every year. These numbers are only for one marine species in one country and thus highlight the global potential for floating construction in the growing sector of offshore aquaculture.

Algae are another specific product from aquaculture which may provide a multitude of solutions to the issues at hand. As algae has significantly higher material yields than any land based crop algal farms offer one of the most efficient uses of space of any crop (Adams, Gallagher, & Donnison, 2009). The versatile use of different algae species is however where the true potential lies. As already mentioned, algae can be processed to produce third generation bio fuel, used as feed for fish and livestock, is suitable for human consumption and also certain pharmaceutical applications (Beal et al., 2015; International Renewable Energy Agency, 2016; Samarakoon & Jeon, 2012; Smit, 2004). Furthermore, these plants can be grown in brackish or salt water and hence neither compete for land nor freshwater resources. Algae also absorb nitrogen, phosphorus and carbon found in wastewater streams as nutrients for their growth and consequently can provide wastewater treatment as well (Abinandan & Shanthakumar, 2015; Dal Bo Zanon, Roeffen, Czapiewska, Graaf-Van Dinther, & Mooij, 2017). A recent discovery has added to this list of beneficial properties of algae. Kinley et al. reported that addition of 2 - 5% of *Asparagopsis taxiformis*, a species of red macro algae, to livestock feed reduces methane production by over 99% in vitro (Kinley, Nys, Vucko, Machado, & Tomkins, 2016). First in vivo tests conducted with sheep showed that addition of 2% algae to the animals feed reduced methane emissions by 50 – 70% over a period of 72 days (Kesteven, 2016). However, it was calculated that to supply enough algae for 10% of Australia's cattle industry 6000 hectares would be necessary (Battaglia, 2016). Therefore, once again floating construction may provide the best opportunity to expand algal farms onto areas large enough to produce the amounts necessary to provide the described benefits on a global scale (Olanrewaju et al., 2016).

It must however also be mentioned that there exist a number of further limitations for large scale expansion of global aquaculture which cannot be solved by moving to the open oceans. For instance, the main obstacle to increasing salmon production in Norway are parasites known as sea lice which reduce growth and increase mortality rates of farmed fish stocks (Bergheim, 2012). Another major challenge for aquaculture growth is the sustainable production of sufficient quantities of feed. Many farmed species – especially carnivorous fish – rely on feed derived from wild fish stocks specifically fish meal and fish oil (Gjedrem et al., 2012; Troell et al., 2014). An option to decrease this dependency on wild fish stocks is to substitute these products in the feed mix by animal or plant protein. However, this leads to aquaculture tying into the agricultural supply chain thus contributing to the issues of increasing land-based food production and cancelling out the potential advantages thought after in the first place (Naylor et al., 2000). Consequently, one of the most important goals for aquaculture is to decouple feed production from wild catches and land-based agriculture. Possible solutions being discussed are the extraction of single cell oils from microorganisms such as algae, or the use of by products from terrestrial animals (meat, bone meal, blood meal) or seafood processing (Naylor et al., 2009). Despite these remaining challenges, the described examples illustrate how floating infrastructure could enable a widespread growth of offshore aquaculture thus indirectly providing a significant contribution to reducing carbon emissions, as well as resource and space requirements of global food production, while potentially even meeting the rising demand in protein heavy nutrition.

Decreasing scarcity of mineral resources (C)

For many countries without large resource deposits supply security is a more immediate and pressing issue than the amount of worldwide ore reserves available. Global distribution of land-based mineral reserves is mostly highly concentrated leading to a handful of countries with large control over global markets for certain raw materials (European Commission, 2014). Due to the criticality of minerals for modern societies and economic development, importing countries are looking for alternative sources to cover their raw material demand. In the course of these investigations deep sea mining (DSM) has reemerged as a possible solution in the medium to long term (Boomsma & Warnaars, 2015; Hein, Mizell, Koschinsky, & Conrad, 2013). In short the process of DSM involves excavation and collection of minerals on the sea floor at depth ranging from 1000-6000 m, transportation of the ore through a riser system to a surface support vessel (SSV) where it is subsequently dewatered and transported to land for further processing in order to extract valuable raw materials. These mineral deposits can be classified into three distinct types, seafloor massive sulfides, polymetallic or manganese nodules and cobalt-rich ferro-manganese crusts. According to a report by ECORYS (ECORYS, 2014), which was conducted in scope of the Blue Mining project of the European Union, DSM could contribute to the expansion of the resource base and increase supply security for a number of essential minerals as shown in Table 4.

Table 4: Potential impact of deep-sea mining on global metal markets (based on data from ECORYS, 2014)

Elements	Impact of Deep-Sea Mining on

	Global Supply	Supply Security for Importing Nations
Copper	Low	Low
Nickel	Low	Low
Zinc	High	Medium
Cobalt	High	High
Manganese	Medium	Medium
Gold	Low	Low
Silver	Low	Low
Platinum Group Metals	Medium	High
Rare Earth Elements	High	High

A central component for advancing the development of the DSM process is the SSV. Larger vessels or platforms could improve the economics of the process in two ways. Firstly, an increased storage capacity would mean less frequent transport of the ore from the site to land will be required, decreasing the costs for additional supply vessels. Furthermore, the transport of dewatered, unprocessed ores is rather inefficient as a large amount of unwanted sediment and minerals is transported with the valuable ore. Larger SSVs could provide room for more equipment allowing more extensive (pre)processing of the ores on site significantly improving the economics of the entire operation (Laugesen, 2016).

Considering the current market prices for most metals and the technological development level of mining equipment, DSM is not yet a commercially viable venture. Most of the activity is focused on exploring potential deposits and assessing their mineral compositions. Worldwide only two licenses have been granted for actual mining of the sea bed and only one company is actually close to beginning extraction (Petersen, Krätschell, & Hannington, 2016). A further major concern surrounding the concept of DSM are the associated environmental impacts, which are still largely unknown (Ramirez-Llodra et al., 2011; van Dover, 2011). A first long term study conducted by GEOMAR shows that even 37 years after a major disturbance ecosystems located at depth of around 4000 m show little to no signs of regeneration (Vanreusel, Hilario, Ribeiro, Menot, & Arbizu, 2016). This leads to the assumption that DSM will have severe long term impacts on deep sea ecosystems. Consequently, this topic is the most controversial in our discussion of the potential of floating construction. It may decrease global conflict potential by decreasing scarcity for a number of major mineral resources. However, increased development of recycling technologies and infrastructure most likely presents a more sustainable approach for expanding the existing resource base of non-producing countries.

Increasing resilience to flooding events (D)

As with other severe weather events, the number of flooding related incidents has increased substantially in the past decades as a result of climate change (Figure 3). Consequently, the resilience of infrastructure to such disasters is an increasingly important consideration for coastal communities. As mentioned, traditional flood protection measures have proven insufficient in many cases over the past decades. Floating construction offers an alternative approach, shifting the goal from fighting against to living with water both for land-based and permanently floating structures. On land buildings can be constructed on buoyant foundations which are connected to mooring pylons. In the case of a flood the entire building can rise with the increasing water level thus dramatically decreasing potential damage. Permanently floating structures (i.e. structures that are always located on a body of water) show the same behavior in case of rising water levels and additionally are unaffected by earthquakes, since they are isolated from the ground. This increased resilience can be highly beneficial for crucial infrastructure functions such as power generation. In addition to the ability to withstand earthquakes, floating power plants located in deeper waters (ca. 100 m) can also survive a subsequent tsunami without damage (Chandler, 2014). Thus, in the event of such natural disasters floating power plants could limit damage and casualties by keeping power running after the event, enabling better emergency responses (Siemens, 2016).

In the long-term future the construction of truly large scale floating islands able to carry entire communities may furthermore eliminate the need for populations affected by sea level rise to relocate to other countries altogether (Olthuis & Keuning, 2010; Watanabe, Wang, Utsunomiya, & Moan, 2004). For example, the Pacific Island nation of Kiribati, which may likely fall victim to see level rise in the next decades is evaluating the construction of such islands as an adaption measure (Lister & Muk-Pavic, 2015). However, the estimated costs of construction greatly exceed the small nation's financial capabilities (Wyett, 2014) underlining the importance of further research into the development of such large scale structures.

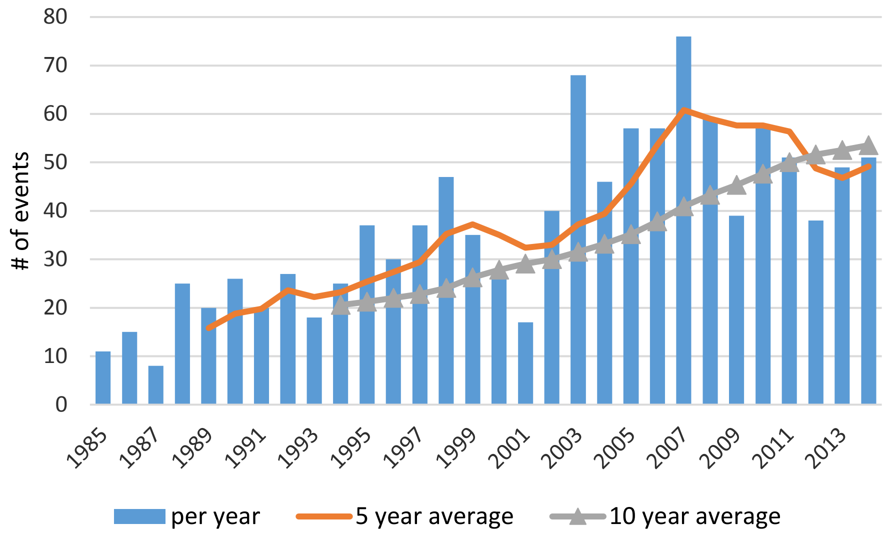

Figure 3: Historical development of extreme flooding events (Brakenridge, 2016)

Urban expansion without land use (E)

The surfaces of lakes, rivers or oceans are largely unoccupied and space on water is abundantly available in most major cities compared to space on land. Around 70% of the earth's surface is covered by oceans, a total area of slightly more than 360 million km^2, which is up to date (with a few exceptions) used solely for transportation of people and goods (Eakins & Sharman, 2010).

Floating construction would open up these spaces for urban expansion consequently mitigating land use conflicts and reducing the necessity for increasing urban population density. Buildings placed on large floating platforms additionally provide urban planners with much needed flexibility in the light of ever increasing magnitude and speed of changes required to provide a satisfactory urban environment. Such changes are usually very difficult to anticipate causing buildings to be demolished as soon as they are no longer required or the specific space can be used more economically by a building of another function. This is often done long before the structural stability of these buildings actually becomes critical. As floating structures are only kept in place by a certain type of mooring it is possible to move them from one position to another, thus eliminating the need for demolition in the wake of urban development. This substantially increases the lifetime of such structures leading to a more efficient use of construction materials and other resources (Olthuis & Keuning, 2010). Considering that waste from construction and demolition is one of the largest waste streams on the planet with 970 million tons produced in Europe alone in 2006 (Monier et al., 2011) and recycling rates for these waste materials ranging from 47% in Europe to a mere 5% in China (Dahlbo et al., 2015; Wu et al., 2016) adaption of this new expansion strategy may greatly improve the sustainability of urban development in the future.

Conclusion

The continued growth of global population and increasing rate of urbanization lie at the heart of the major challenges facing humanity in the coming decades. Climate change as one of these grand challenges will have severe effects on the wellbeing of billions of people around the world, either directly, through for instance rising sea levels and increasingly frequent extreme weather events, and indirectly through increasing global conflict potential. Along with other more established mitigation and adaption strategies floating construction may form a crucial piece of a possible solution. Implemented on a larger scale, floating construction has the ability to improve the performance of renewable energy generation, increase more efficient food production by enabling widespread growth of offshore aquaculture and (if feasible from an environmental perspective) provide access to extensive mineral reserves located on the bottom of the ocean. Furthermore, it will also play an important role in increasing the resilience of coastal communities by minimizing damage to central infrastructure functions caused by increasingly frequent and severe flooding events. Finally, in the longer term floating construction has the potential to mitigate land use conflict as it opens up the vast areas of the planet which are covered by water for sustainable urban expansion. Naturally, these different areas of application will involve various types and designs of floating structures depending on their specific requirements. This will also necessitate the use of a large amount of different construction materials in order to meet these requirements of individual components. The marine environment is one of the most hostile environments concerning material degradation due to corrosiveness, the occurrence of wetting and drying cycles, thriving biological activity and high loads from wind and waves (Pilson, 2013). As local conditions vary from area to area and season to season, the accurate prediction of lifetimes for marine structures is very challenging (Alexander, 2016; Powell & Francis, 2012). One step towards improving the overall viability and also sustainability of floating infrastructure is the development of more accurate prediction models (Angst et al., 2012). In a further step the use and development of environmentally friendly protection strategies for existing materials and the development of intrinsically more resistant materials will be of paramount importance for the widespread adoption of this construction approach. Furthermore, in order to focus, from the beginning, on developing sustainable and economically viable materials and solutions, the long-term availability of all required raw materials needs to be taken into consideration already today. Finally, another barrier to the large scale introduction of floating infrastructure is a lack of funding mainly due to the risk associated with the high installation costs and missing regulatory framework for such applications (Díaz, Rodrigues, & Guedes Soares, 2016). Exploring legal and insurance aspects of floating structures in coastal areas as well as international waters will be necessary to increasing investments by governments and private companies. The existence of large floating oil-rigs for offshore drilling, full scale prototypes of floating wind turbines and also multistory floating houses serves as a clear demonstration that the associated engineering challenges can be solved. Nevertheless, despite the discussed benefits of floating construction, the impact of larger structures on the surrounding environment must be explored in greater detail before extensive areas of open water are covered. Thorough investigation of the impacts of floating structures has only just begun. Early results are very positive, pointing towards the fact that these structures actually provide additional hiding space as well as anchoring surfaces to different marine animals (Foka et al., 2015; Wilhelmsson, Malm, & Ohman, 2006). In light of the great potential floating construction may have for future generations, research into the areas described in this study should be of interest to governments and cities aiming at mitigating and adapting to the effects of global climate change.

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